SLAC-PUB-95-6762

Moduli Inflation from Dynamical Supersymmetry Breaking

Scott Thomas[†]

Stanford Linear Accelerator Center
Stanford University
Stanford, CA 94309

Moduli fields, which parameterize perturbative flat directions of the potential in supersymmetric theories, are natural candidates to act as inflatons. An inflationary potential on moduli space can result if the scale of dynamical SUSY breaking in some sector of the theory is determined by a moduli dependent coupling. The magnitude of density fluctuations generated during inflation then depends on the scale of SUSY breaking in this sector. This can naturally be hierarchically smaller than the Planck scale in a dynamical model, giving small fluctuations without any fine tuning of parameters. It is also natural for SUSY to be restored at the minimum of the moduli potential, and to leave the universe with zero cosmological constant after inflation. Acceptable reheating can also be achieved in this scenario.

Submitted to Physics Letters B

[†]Work supported by the Department of Energy under contract DE-AC03-76SF00515.

1 Introduction

The existence of an inflationary phase in the early universe, dominated by vacuum energy, eliminates the flatness and horizon problems of standard big bang cosmology [1, 2]. In addition, any preexisting topological defects such as monopoles can be diluted. Conversion of the vacuum energy to radiation after inflation acts as the source of entropy for our universe. In addition, quantum deSitter fluctuations of the inflaton field(s) driving inflation imprint a (nearly) scale invariant spectrum of fluctuations on the background space time metric, which can act as seeds for structure formation. The inflaton must be weakly coupled in order that these fluctuations do not spoil spatial isotropy. In fact, to be consistent with the density and temperature fluctuations observed in the present universe, $\delta\rho/\rho \sim \delta T/T \sim 10^{-5}$, the inflaton potential must be extremely flat, with a very small dimensionless self coupling, $\lambda \sim 10^{-8}$. All models of inflation must contain such a small coupling [2]. In this paper I outline a scheme in which moduli act as inflatons. The small self coupling arises naturally from dynamical SUSY breaking.

The requirement of introducing a small parameter to ensure that the inflaton potential is extremely flat makes models of inflation seem fine tuned and unnatural. In order to be even technically natural the couplings of the inflaton to other fields must also be very small in non-supersymmetric theories. Otherwise the small self coupling would not be stable quantum mechanically. Technical naturalness can be achieved though in supersymmetric models [3]. The nonrenormalization theorem guarantees that the superpotential is not renormalized to all orders in perturbation theory [4]. The Kahler potential is renormalized but this amounts effectively only to wave function renormalization. The functional form of the resulting potential, including the inflaton self coupling, is therefore stable even if the inflaton has couplings to other fields. This special property of supersymmetry has been exploited to construct models of inflation within supergravity [5], supersymmetric GUT

theories [6], hidden sector models of supersymmetry breaking [7], and superstring theories [8, 9]. However most of these models seem aesthetically unnatural since the small parameter, λ, must be input by hand to obtain a reasonable value for $\delta\rho/\rho$.

Here I point out that the existence of exact perturbative flat directions and dynamical SUSY breaking can lead to an acceptable inflationary potential with small self coupling. The potential along certain directions in field space can vanish perturbatively in the supersymmetric limit. The vanishing of the perturbative potential for moduli makes $\lambda \ll 1$ technically natural. More important, a nonzero moduli potential can result from nonperturbative dynamics which breaks supersymmetry at a scale μ. If there is a moduli dependent coupling which determines the SUSY breaking scale μ, the moduli can act as inflatons with vacuum energy set by the scale μ^4. Assuming the couplings between the moduli and SUSY breaking sector are generated at the Planck scale, M_p, the moduli self coupling arises as the ratio $\lambda \sim (\mu/M_p)^4$. Since the scale μ arises dynamically by dimensional transmutation, it can be hierarchically smaller than the Planck scale, and a small self coupling arises naturally. SUSY breaking in the sector responsible for driving inflation can naturally vanish at the minimum of the moduli potential, with zero cosmological constant, as discussed below. The scale μ is then in principle unrelated to the scale of SUSY breaking responsible for the mass splittings within the standard model supermultiplets.

In the next section I describe how moduli can act as inflatons with a potential induced by SUSY breaking in some sector of the theory. Section 3 gives a simple model of dynamical SUSY breaking which generates a potential on moduli space. In this model SUSY breaking and the cosmological constant vanish at the minimum of the moduli potential. The final section addresses reheating after inflation.

2 Inflation on Moduli Space

Supersymmetric theories can have noncompact flat directions in field space on which the exact classical superpotential vanishes. The fields parameterizing such flat directions are generally referred to as moduli. In field theory, moduli can arise as the result of a discrete (or continuous) R symmetry. Under a discrete Z_N R symmetry the superpotential transforms as $W \to e^{4\pi i/N} W$. If a modulus, $\mathcal{M}$, is a singlet under such a symmetry, it can not appear alone in the tree level superpotential to any power [10]. An exact continuous global symmetry can also guarantee the potential vanishes along some directions [11]. In superstring theory world sheet symmetries can give rise to flat directions. For example, in (2,2) compactifications, amplitudes involving only moduli which describe deformations of the internal Calabi-Yau manifold vanish at zero momentum [12]. These moduli therefore do not appear alone to any power in the superpotential. The nonrenormalization theorem guarantees that the superpotential is not renormalized by quantum corrections at any order in perturbation theory [4]. The classical degeneracy of the potential for moduli is therefore preserved to all orders perturbatively. Since the perturbative potential vanishes for moduli, these are the natural candidates for inflatons in supersymmetric theories [8, 11].

It is supersymmetry which protects the moduli from obtaining a perturbative potential. A nontrivial potential necessary for inflation therefore requires supersymmetry breaking. The simplest mechanism by which a SUSY breaking potential can be induced on moduli space is for some parameters which describe the magnitude of a SUSY breaking scale, μ, to depend on the moduli. The SUSY breaking potential is then moduli dependent. As discussed in the next section, within field theory, moduli dependent couplings can arise from the same R symmetry that protects the moduli from obtaining a potential in the supersymmetric limit. In string theory it is common for couplings to be moduli dependent. It is therefore quite natural for the scale

of SUSY breaking in some sector to have moduli dependence.

If the couplings between the SUSY breaking and moduli sectors are suppressed by the Planck scale (as would be the case for string moduli) the (dimensionless) parameters in the SUSY breaking sector vary by $\mathcal{O}(1)$ as the moduli vary by $\mathcal{O}(M_p)$. The Planck mass then sets the scale for variations of the potential on moduli space

$$V(\mathcal{M}) = \mu^4 \mathcal{F}(\mathcal{M}/M_p) \tag{1}$$

where μ is the scale of SUSY breaking during inflation, $\mathcal{F}$ is some model dependent function, and $M_p = m_p/\sqrt{8\pi}$ is the reduced Planck Mass. This leads to a moduli self coupling of $\lambda \sim (\mu/M_p)^4$, and Hubble constant during inflation of $H \simeq (\mathcal{F}/3)^{1/2}(\mu^2/M_p)$. The resulting density fluctuations are $\delta\rho/\rho \simeq (\sqrt{75}\pi)^{-1}(\mathcal{F}^{3/2}/\mathcal{F}')(\mu/M_p)^2$ [13], and quadrapole temperature fluctuation $\delta T/T \simeq \sqrt{5/48}(\delta\rho/\rho)$ [14]. The correct magnitude for density and temperature fluctuations results for $\mu \sim 10^{16}$ GeV, giving a Hubble constant during inflation of $H \sim 10^{14}$ GeV. During inflation the moduli kinetic energy is insignificant and the slow roll equation gives $\dot{\mathcal{M}} \simeq -HM_p(\mathcal{F}'/\mathcal{F})$. The modulus acting as inflaton therefore changes by $\mathcal{O}(M_p)$ during one expansion time. In order to maintain the functional form (1) as $\mathcal{M}$ evolves during inflation, the tree level superpotential must therefore vanish essentially to all orders in M_p^{-1} [11]. As discussed above, this can occur as the result of field theory or string symmetries.

Inflaton potentials with the functional form (1) have been considered previously, with the scale μ input by hand [15]. However, here μ is generated by nonperturbative SUSY breaking in some sector of the theory. Since this scale arises dynamically as the result of dimensional transmutation, it can be hierarchically smaller than the Planck scale. No small parameters are input into the theory (as shown explicitly in the next section) and a small but finite inflaton self coupling arises naturally. No fine tuning is required.

In order to avoid excessive SUSY breaking in the present universe, the

dynamical SUSY breaking responsible for driving inflation in the moduli sector should vanish at the minimum of the moduli potential. This can arise naturally if the scale of dynamical SUSY breaking, μ, is controlled by a single moduli dependent parameter, $\xi(\mathcal{M})$. It is possible for the range of $\xi(\mathcal{M})$ to include a value for which SUSY is unbroken. The moduli potential then vanishes on some subspace, $V(\mathcal{M}_-) = 0$, and inflation ceases on $\mathcal{M}_-$ (assuming the cosmological constant vanishes after inflation). The scale of SUSY breaking should depend on a single parameter in this scenario since generically multiple parameters will not simultaneously vanish on a subspace of moduli space.

It is important in this scheme that SUSY breaking in the sector responsible for driving inflation does in fact vanish at the minimum of the moduli potential. Otherwise this SUSY breaking would remain after inflation and be transmitted in the present universe to the visible sector by (at least) gravitational strength interactions. In such a hidden sector scenario for producing the "observed" visible sector SUSY breaking, μ must be identified with the intermediate scale, $\mu \sim \sqrt{m_{3/2} M_p} \sim 10^{10-11}$ GeV, where $m_{3/2}$ is the gravitino mass. While this may be a natural scale for inflation on moduli space, it leads to a Hubble constant during inflation of $H \sim m_{3/2}$. Such an inflationary epoch can have interesting cosmological consequences, but generates very small density fluctuations, $\delta\rho/\rho \sim (m_{3/2}/M_p) \sim 10^{-16}$ [11].

3 A Dynamical Model for the Inflaton Potential

As an example of the scheme outlined above I consider a simple field theory model. The model illustrates the important feature of a single moduli dependent parameter which controls dynamical SUSY breaking. For the sector of the theory which breaks supersymmetry during inflation I take the model

of Intriligator, Seiberg, and Shenker [16]. This model contains a single matter field, Q, transforming as spin $\frac{3}{2}$ under $SU(2)$. The lowest order $SU(2)$ invariant superpotential is nonrenormalizable

$$W = \frac{\beta}{M_p} Q^4 \tag{2}$$

where I assume this term is generated at the Planck scale. The Kahler potential for the flat direction in this sector, $X = Q^4$, has a classical singularity at the origin, $K = (\bar{X}X)^{1/4}$. The singularity is believed to be smoothed out for small X by nonperturbative quantum effects, giving $K \simeq (\bar{X}X)/\Lambda^6$, where Λ is related to the $SU(2)$ dynamical scale $\Lambda \sim \Lambda_2 = M_p e^{-8\pi^2/bg^2(M_p)}$, and b is coefficient of the one loop beta function [16]. In the presence of the superpotential (2), this leads to supersymmetry breaking with $Q = 0$ and vacuum energy (in the global limit) of $V = \beta^2 \Lambda^6 / M_p^2$. Note that for $g(M_p) \sim \mathcal{O}(1)$, Λ is hierarchically smaller than M_p. No fine tuning is required to obtain a SUSY breaking scale much less than the Planck scale. This model amounts to nonrenormalizable SUSY breaking since the breaking scale, $\mu^2 \sim \Lambda^3/M_p^2$, vanishes in the $M_p \to 0$ limit [17]. Whether the SUSY breaking sector which generates the potential on moduli space is renormalizable or nonrenormalizable is not important.

For the moduli sector I take a single chiral superfield $\mathcal{M}$. The modulus $\mathcal{M}$ can be either an elementary singlet field, or a composite field parameterizing an exact flat direction in some other sector. As discussed in the previous section, tree level terms involving any power of $\mathcal{M}$ can be guaranteed to vanish if the superpotential is invariant under a discrete (or continuous) R symmetry, and $\mathcal{M}$ does not transform. For example, the discrete Z_3 R symmetry $Q \to e^{i\pi/3} Q$, $\mathcal{M} \to \mathcal{M}$, forbids self couplings of $\mathcal{M}$ while

$$W = \frac{1}{M_p} f(\mathcal{M}/M_p) Q^4 \tag{3}$$

is allowed, where f is some holomorphic function. Over all of moduli space $Q = 0$ is stable and $\partial W / \partial \mathcal{M} = 0$ [18]. The potential on moduli space arises

solely from the F component in the Q sector, $\partial W/\partial Q \neq 0$. As long as β is in the range of f, there is (at least) one point on the moduli space $\mathcal{M}$ for which the vacuum energy vanishes and supersymmetry is unbroken in the Q sector. Including supergravity interactions, and neglecting any coupling between Q and $\mathcal{M}$ in the Kahler potential, the potential for $\mathcal{M}$ with $Q = 0$ is of the form (1)

$$V(\mathcal{M}) = \frac{\Lambda^6}{M_p^2} e^{K(\mathcal{M},\bar{\mathcal{M}})/M_p^2} |\xi(\mathcal{M}/M_p)|^2 \tag{4}$$

where $\xi = f + \beta$ and $K(\mathcal{M}, \bar{\mathcal{M}})$ is the modulus Kahler potential [19]. If K and ξ are such that the slow roll conditions are satisfied, inflation can result. A moderate amount of tuning of K and ξ is required in order to obtain a sufficient number of e-foldings to solve the horizon and flatness problems. But this is true of any model of supersymmetric inflation [20]. The modulus self coupling and Hubble constant are related in this model to Λ by $\lambda \sim (\Lambda/M_p)^6$ and $H \sim \Lambda^3/M_p^2$. A dynamical scale of $\Lambda \sim 10^{16.5}$ GeV gives the correct magnitude for density fluctuations. Notice that since $\Lambda \gg H$ during inflation, deSitter fluctuations do not destroy the nonperturbative effects in the Q sector.

This model has the interesting property that the expectation value of the superpotential vanishes. The full supergravity potential, $V = e^{K/M_p^2}\left(DW\bar{D}W - 3|W|^2/M_p^2\right)$, therefore vanishes at the supersymmetric minimum, leaving the universe with zero cosmological constant after inflation. The importance of obtaining $\langle W \rangle = 0$ at a supersymmetric stationary point ($DW = 0$) has recently been emphasized by Banks, Berkooz, and Steinhardt in the context of the Polonyi problem [21]. A nonzero expectation value for the superpotential gives a negative contribution to the cosmological constant, $-3e^{K/M_p^2}|W|^2/M_p^2$. If this were the case in the present context, the universe would enter a phase of irreversible contraction after inflation [21]. The model above naturally avoids this problem since the stationary point is

$Q = 0$ giving $\langle W \rangle = 0$ during and after inflation. The cosmological constant therefore automatically vanishes after inflation.

The scheme outlined above for obtaining a potential on moduli space could be extended to other models. For example, many dynamical models contain a single Yukawa coupling, h, which controls the vacuum energy [22]. Moduli dependence of this coupling, $h(\mathcal{M})$, would lead to a potential on moduli space. However in many models of this type the supersymmetric point corresponds to $h(\mathcal{M}) \to \infty$. For field theory moduli this would usually not correspond to a finite point on moduli space. For string theory moduli this typically represents a singular limit. In addition there is often a minimum at finite $h(\mathcal{M})$ but with SUSY broken in the moduli sector. Such models therefore do not seem to give acceptable potentials for the moduli to act as inflatons. Dynamical models in which SUSY breaking vanishes at some finite value of a parameter (such as in the model above) can have a SUSY preserving minimum with zero cosmological constant at a finite point on moduli space.

4 Reheating After Inflation

As the inflaton evolves toward the minimum of the potential, the slow roll conditions must eventually break down, and inflation will cease. The universe then enters an era dominated by the coherent oscillations of the inflaton. The inflaton eventually decays, reheating the universe. After inflation, $\mathcal{M} \ll M_p$, and the inflaton oscillates in a potential $V(\mathcal{M}) \simeq \mu^4 |\xi(\mathcal{M})|^2$. If the modulus acting as inflaton is an elementary singlet, and $\xi'(\mathcal{M}_-) \neq 0$, the oscillations are harmonic with a mass $\sim \mu^2/M_p$. The modulus can have Planck scale suppressed couplings to visible sector fields. This results in a decay rate

$$\Gamma \sim \frac{\mu^6}{8\pi M_p^5} \tag{5}$$

giving a reheat temperature of $T_R \sim \sqrt{\Gamma M_p} \sim 10^{10-11}$ GeV.

One requirement for a successful inflationary scenario is that any particles with weak scale mass and Planck suppressed couplings not be overproduced after inflation. Examples of such fields include the gravitino [23] and scalar moduli, usually referred to as Polonyi fields in this context [24]. The late decay of these fields can ruin the successful predictions of nucleosynthesis. The large reheat temperature resulting from (5) is just barely compatible with a conservative estimate of the bound arising from thermal production of gravitinos and Polonyi fields [23, 25]. However, the production of these fields directly in the inflaton decay chain (which may include hidden sector fields) must also be avoided [25]. The direct decay to gravitinos suffers a helicity suppression $(m_{3/2}/M_p)^2$ as compared to (5). The direct decay to Polonyi fields is not suppressed though. In addition, supergravity interactions can lead to production of Polonyi fields by parametric resonance with the oscillating inflaton [26, 27]. Either production mechanism would lead to a postinflationary universe eventually dominated by nonrelativistic Polonyi fields.

This version of the Polonyi problem is probably generic to most models of inflation, but might be avoided in a number of ways. The Polonyi fields can obtain a mass from nonperturbative dynamics not related to $m_{3/2}$ [21]. In this case these fields either decay before nucleosynthesis or are too heavy to be produced in the inflaton decay. This is perhaps natural in the context of moduli inflation since any singlet modulus which couples to the SUSY breaking sector responsible for driving inflation gains a mass of order μ^2/M_p. Alternately, the modulus acting as inflaton could have larger than Planck suppressed couplings to the visible sector. This occurs if the inflaton is a composite flat direction made directly of n standard model fields, $\mathcal{M} = \phi^n$, where ϕ is a canonically normalized field. The smallest value of n is 2 for the flat directions $H_u H_d$ and LH_u. As long as $\xi'(\mathcal{M}_-) \neq 0$ the potential in which

such a composite inflaton oscillates after inflation is $V(\phi) \sim \mu^4(\phi/M_p)^{2n}$. Pure supergravity couplings of the composite flat direction to other fields give a decay rate that goes like $\Gamma \sim \omega^3/8\pi^2 M_p^2$, where $\omega \sim (\mu^2\langle\phi\rangle^{n-1}/M_p^n)$ is the inflaton oscillation frequency. The decay rate through such couplings then scales like

$$\frac{\Gamma}{H} \sim \left(\frac{H_{\rm inf}}{M_p}\right)^2 \left(\frac{H}{H_{\rm inf}}\right)^{(2n-3)/n} \ll 1$$

where $H_{\rm inf} \sim \mu^2/M_p$ is the Hubble constant during inflation, and $H < H_{\rm inf}$ is the time dependent Hubble parameter after inflation. So a composite inflaton can not efficiently decay through Planck suppressed couplings. In particular, it does not decay to gravitinos or Polonyi fields. The other way the flat direction can decay is through its Yukawa couplings to other standard model fields. The states coupled by a Yukawa coupling, g, gain a mass $g\langle\phi\rangle$ while the flat direction is oscillating. The ratio of the mass of these states to the inflaton oscillation frequency is

$$\frac{g\langle\phi\rangle}{\omega} \sim g \left(\frac{M_p}{H_{\rm inf}}\right) \left(\frac{H_{\rm inf}}{H}\right)^{(n-2)/2}$$

This implies that unless $n = 2$ and $g < 10^{-4}$, $g\langle\phi\rangle > \omega$, and decays through the Yukawa coupling are kinematically suppressed during this epoch. However, when the SUSY breaking potential arising from hidden sector breaking becomes important, $V(\phi) \sim m_{3/2}^2\phi^*\phi$, the flat direction can eventually decay through the Yukawa coupling with a reheat temperature $T_R \sim m_{3/2}/\sqrt{g}$ [11]. The decay of a standard model flat direction apparently does not contribute to the Polonyi problem, and has a reheat temperature just above the weak scale.

5 Conclusions

The potential of the field responsible for driving inflation must be exceedingly flat. Supersymmetric moduli, with vanishing perturbative potentials, are

therefore natural candidates to act as inflatons. Dynamical nonperturbative SUSY breaking lifts the moduli, giving a small but nonvanishing potential. Moduli inflation therefore solves the naturalness and fine tuning problems of inflation [28]. It may be possible to construct intricate models in which the scale for the potential on moduli space is related to hidden sector SUSY breaking, while still giving acceptable density fluctuations. However, in the simplest models supersymmetry is restored at the minimum of the moduli potential. The inflation scale is then unrelated directly to any low energy scale.

I would like thank T. Banks, M. Dine, A. Guth, V. Rubakov, and S. Shenker for useful discussions about inflation, and especially R. Leigh for pointing out the potential problem of reheating the hidden sector. I also would like to thank the Rutgers high energy theory group for its hospitality during completion of this work. During completion of this paper I became aware of related work [29] which considers the possibility of moduli inflation.

References

[1] A. Guth, Phys. Rev. D **23** (1981) 347; A. Linde, Phys. Lett. B **108** (1982) 389; A. Albrecht and P. Steinhardt, Phys. Rev. Lett. **48** (1982) 1220.

[2] For recent reviews of inflation see A. Linde, *Particle Physics and Inflationary Cosmology* (Harwood Academic, New York, 1990); E. Kolb and M. Turner, *The Early Universe* (Addison-Wesley, New York, 1990); K. Olive, Phys. Rep. **190** (1990) 307.

[3] J. Ellis, D. Nanopoulos, K. Olive, and K. Tamvakis, Phys. Lett. B **118** (1982) 335.

[4] M. Grisaru, W. Siegel, and M Rocek, Nucl. Phys. B **159** (1979) 429; N. Seiberg, Phys. Lett. B **318** (1993) 469.

[5] R. Holman, P. Ramond, and G. Ross, Phys. Lett. B **137** (1984) 343; J. Ellis, K. Enqvist, D. Nanopoulos, K. Olive, and M. Srednicki, Phys. Lett. B **152** (1985) 175; K. Kumekawa, T. Moroi, and T. Yanagida, preprint TU-458, hep-ph 9405337.

[6] A. Albrecht, S. Dimopoulos, W. Fischler, E. Kolb, S. Raby, and P. Steinhardt, Nucl. Phys. B **229** (1983) 528; A. Albrecht and P. Steinhardt, Phys. Lett. B **131** (1983) 45; B. Gato, J. León, M. Quirós, and M. Ramón-Medrano, Z. Phys. C **22** (1984) 345; G. Dvali, Q. Shafi, and R. Schaefer, Phys. Rev. Lett. **73** (1994) 1886.

[7] B. Ovurt and P. Steinhardt, Phys. Rev. Lett. **53** (1984) 732; Phys. Rev. D **30** (1984) 2061; P. Binétruy and S. Mahajan, Nucl. Phys. B **263** (1986) 413; O. Bertolami and G. Ross, Phys. Lett. B **171** (1986) 46.

[8] P. Binétruy and M. K. Gaillard, Phys. Rev. D **34** (1986) 3069.

[9] F. Graziani and K. Olive, Phys. Rev. D **38** (1988) 2386; B. Campbell, A. Linde, and K. Olive, Nucl. Phys. B **355** (1991) 146; E. Stewart, preprint KUNS 1261, hep-ph 9405389; A. De La Macorra and S. Lola, preprint IFUNAM-FT-94-63, hep-ph 9411443.

[10] M. Dine and N. Seiberg, Nucl. Phys. B **306** (1988) 137; M. Dine, *private communication.*

[11] L. Randall and S. Thomas, preprint MIT-CTP-2331, SCIPP 94-16, hep-ph 9407248.

[12] L. Dixon, in *Superstrings, Unified Theories, and Cosmology 1987*, Proceedings of the Summer Workshop in High Energy Physics and Cosmol-

ogy, eds. G. Furlan *et. al.*, (World Scientific, Singapore, 1987); L. Dixon, V. Kaplunovsky, and J. Louis, Nucl. Phys. B **329** (1990) 27.

[13] J. Bardeen, P. Steinhardt, and M. Turner, Phys. Rev. D **28** (1983) 679; D. H. Lyth, Phys. Rev. D **31** (1985) 1792; A. Liddle and D. Lyth, Phys. Rep. **231** (1993) 1.

[14] P. J. E. Peebles, Ap. J. **263** (1982) L1; L. Abbott and M. Wise, Phys. Lett. B **135** (1984) 279.

[15] D. Nanopoulos, K. Olive, M. Srednicki, and K. Tamvakis, Phys. Lett. B **123** (1983) 41; A. D. Linde, Phys. Lett. B **129** (1983) 177; A. Albrecht and R. Brandenberger, Phys. Rev. D **31** (1985) 1225; J. Ellis, K. Enqvist, D. Nanopoulos, and K. Olive, Phys. Lett. B **191** (1987) 343.

[16] K. Intriligator, N. Seiberg, and S. Shenker, preprint RU-94-75, IASSNS-HEP-94-79, hep-ph 9410203.

[17] T. Banks, D. Kaplan, and A. Nelson, Phys. Rev. D **49** (1994) 779.

[18] The potential for small Q along the direction Q^4 is flat to lowest order in the global limit. During inflation supergravity corrections lift this local degeneracy making $Q = 0$ stable. Terms higher order in Q^4 in the superpotential do not affect the SUSY breaking state at $Q = 0$.

[19] Inclusion of Kahler potential couplings between the moduli and SUSY breaking sectors would not change the parametric dependences in the potential.

[20] It is possible to choose Kahler potentials which minimize the required fine tuning. E. Stewart, preprint KUNS-1286, hep-ph 9408302.

[21] T. Banks, M. Berkooz, and P. Steinhardt, preprint RU-94-92, hep-th 9501053.

[22] I. Affleck, M. Dine, and N. Seiberg, Nucl. Phys. B **256** (1985) 557; D. Amati, K. Konishi, Y. Meurice, G. Rossi, and G. Veneziano, Phys. Rep. **162** (1988) 169; A. Nelson and N. Seiberg, Nucl. Phys. B **416** (1994) 46.

[23] J. Ellis, A. Linde, and D. Nanopoulos, Phys. Lett. B **118** (1982) 59; D. Nanopouolos, K. Olive, and M. Srednicki, Phys. Lett. B **127** (1983) 30; J. Ellis, J. Kim, and D. Nanopoulos, Phys. Lett. B **145** (1984) 181. For recent discussions of the gravitino problem see M. Kawaski and T. Moroi, preprint hep-ph 9403364; W. Fischler, Phys. Lett. B **332** (1994) 277.

[24] G. Coughlan, W. Fischler, E. Kolb, S. Raby, and G. Ross, Phys. Lett. B **131** (1983) 59; J. Ellis, D. Nanopoulos, and M. Quirós, Phys. Lett. B **174** (1986) 176.

[25] R. Leigh and R. Rattazzi, preprint RU-94-100; R. Leigh, *private communication*.

[26] L. Kofman, A. Linde, and A. Starobinsky, Phys. Rev. Lett. **73** (1994) 3195; Y. Shtanov, J. Traschen, and R. Brandenberger, preprint BROWN-HET-957, hep-ph 9407247.

[27] Resonant production of visible sector fields is unlikely since the large scattering cross section would destroy coherence.

[28] The naturalness of moduli inflation is similar to that for pseudo-Goldstone boson inflation. There the dynamical breaking of a nonlinearly realized global symmetry gives a small potential to a Goldstone boson. K. Freese, J. Frieman, and A. Olinto, Phys. Rev. Lett. **65** (1990) 3233.

[29] T. Banks, M. Berkooz, G. Moore, S. H. Shenker, and P. J. Steinhardt, preprint RU-94-93.